LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

CONF-870121--5

LA-UR -87-1196

LA-UR--87-1196

DE87 008990

TITLE LIMITS ON THE ELECTRON-ANTINEUTRINO MASS

AUTHOR(S) J. F. Wilkerson

SUBMITTED TO The APS Division of Particles and Fields Meeting, January 15, 1987

Los Alamos Los Alamos National Laboratory Los Alamos, New Mexico 87545

FORM NO. 836 R4
ST. NO. 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LIMITS ON THE ELECTRON-ANTINEUTRINO MASS

J. F. Wilkerson

Physics Division, Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

New measurements near the endpoint of the tritium beta-decay spectrum are producing limits on the electron-antineutrino mass which are below the central mass value of 30 eV reported by ITEP[1]. The factors that influence the neutrino mass sensitivity of tritium beta decay measurements will be discussed followed by a review of the current experimental results.

1. INTRODUCTION

It has been nearly seven years since the report by the ITEP group in Moscow of evidence for a non-zero $\bar{\nu}_e$ mass from measurements near the endpoint of the tritium beta decay spectrum[2]. Motivated by this result a number of new tritium beta decay experiments were begun and during 1986 a few of these experiments reported their first results. Table 1 gives a list of tritium beta decay experiments that are currently active. From this table it is clear that we may expect many new results during the next few years from experiments using radically different sources and quite diverse measurement techniques.

The important consequences a non-zero neutrino mass would have in our understanding of physics demand that each experiment, independent of its results, be carefully examined. However, to perform a careful evaluation of any these experiments requires understanding the factors that influence the neutrino mass sensitivity. Thus, measurement considerations will be discussed before reviewing the experiments that have reported results.

EHB

Table 1.

Investigator	Location	Spectrometer	Source	Status*
Lyubimov (ITEP)	Moscow	Toroidal Mag	Valine-T	R
Bowles, Robertson, JFW	Los Alamos	Toroidal Mag	T_2, T gas	R
Kundig	Zurich	Toroidal Mag	C-T	R
Stoeffl	Livermore	Toroidal Mag	T_2, T gas	U
Ohshima (INS)	Tokyo	$\pi\sqrt{2}$ Mag	Arachidic Acid-T	R
Sun (IAE)	Beijing	$\pi\sqrt{2}$ Mag	PAD organic	P
Daniel	Munich	$\pi\sqrt{13/2}$ mag	Hf-T	P
Clark, Frisch	Yorktown (IBM)	Retarding E-S	?-T	T
Fackler	Livermore	Retarding E-S	Al_2O_3-T, T_2 solid	T
Lobashev	Moscow	Retarding E-S	T_2, T gas	U
Bonn, Otten	Mainz	Retarding E-S	T_2, T gas	U
Boyd	Columbus	Retarding E-S	T_2 solid	U
Jelly	Oxford	Cyl Mirror E-S	Cd Palmitate-T	T
Wellenstein	Brandeis	Cyl Mirror E-S	T_2 gas	U
Simpson	Guelph	Silicon	Si-T	C
Derbin-Popeka	Leningrad	Silicon	Si-T	C
Shang	Beijing	Silicon	Si-T	P

* R = Result P = Preliminary Result T = Testing U = Under construction C = Complete

2. TRITIUM BETA DECAY MEASUREMENT CONSIDERATIONS

Tritium beta decay experiments are sensitive to $\overline{\nu}_e$ mass in the energy region of the beta spectrum from a few m_ν below the endpoint energy to the endpoint energy, E_0, of the decay. The actual experimental procedure is to measure the energy region about the endpoint and also far below the endpoint. Then, the curve derived from extrapolating to the endpoint from the measurements far below the endpoint can be compared with the measurements near the endpoint

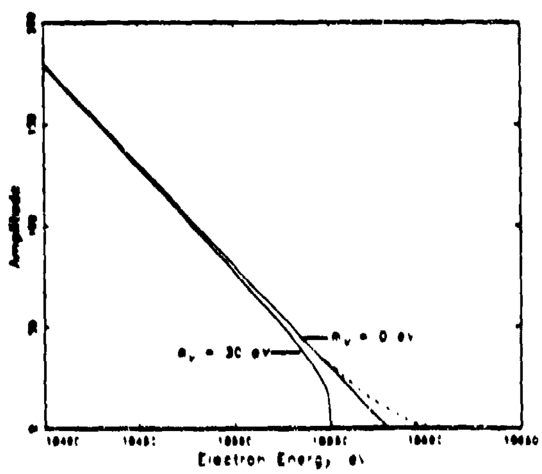

Fig. 1. Kurie plot showing the effect of neutrino mass on the beta spectrum of tritium. The dashed line represents the influence of resolution smearing and atomic final state effects.

yielding a sensitive determination of the neutrino mass. This effect is illustrated in Fig. 1 where Kurie plots of tritium decay spectra assuming m_ν = 0 eV and m_ν = 30 eV are shown for the energy region around E_0. This limited region of $\bar{\nu}_e$ mass sensitivity imposes two principal difficulties on any attempt to make a measurement. First, the decay rate in the energy region near the endpoint is a very small fraction of the total decay rate. For example, the decay rate in the last 100 eV of the spectrum below E_0 is about 2×10^{-7} the total decay rate. Thus, acquiring sufficient statistics with good signal-to-background (S:B) is one of the primary consideracions in making a tritium beta decay measurement.

The second consideration for a measurement is that all possible systematic effects which modify the beta spectrum must be accurately accounted for. Notice in Fig. 1 that in the Kurie plot representation, (a linearization of the beta decay probability function) one expects that for the ideal case the zero neutrino mass decay spectrum is a straight line while the finite neutrino mass decay spectrum curves downwards. However, in actual measurements, resolution broadening effects and decays to the different atomic final states of the source introduce an upward curvature to the measured decay spectrum (the dashed curve in Fig. 1). Thus, one must accurately account for all possible systematic effects, since an underestimation of these effects will result in an underestimation of the neutrino mass and conversely an overestimation of the effects results in an overestimation of the neutrino mass.

2.1 Systematic Effects

Systematic effects are either source related or of instrumental origin. All sources introduce energy loss and final state systematic effects into a beta spectrum measurement. Solid sources may have additional non-negligible contributions from backscattering and surface contamination. Instrumental systematic effects include the finite energy resolution of the system and possibly energy-dependent extraction efficiencies.

Because the elimination of most of these systematic effects is impossible, one would like to minimize and accurately account for them in a model independent manner. It is clearly preferable to design into the experiment the capability to explicitly measure these effects since calculations often introduce model dependencies and the corresponding uncertainties in the determination of m_ν.

2.1.1 Final state effects. When a tritium atom decays to a $^3He^+$ ion there is a probability of populating any of the energetically allowed atomic final states of the daughter $^3He^+$ ion. The observed beta spectrum is actually the sum of all of the individual branches to all possible final states. Extracting a reliable value for m_ν requires the precise knowledge of the branching ratios and the energies for all possible final decay states. This is because the reported neutrino mass is of the same order as the binding energy of electrons in ^3He.

The only sources for which the decay probabilities can be accurately determined are for atomic tritium[3] and molecular tritium[4,5] where the uncertainties are at the level of ~1 eV. For complex sources such as the tritiated valine molecule used by the ITEP group[1] or tritium implanted in carbon used in the Zurich experiment[6] the final state effects are difficult to calculate and exact calculations are impossible. Hence, model dependent uncertainties are introduced into the m_ν value or limit for all sources except ionic, atomic or molecular tritium.

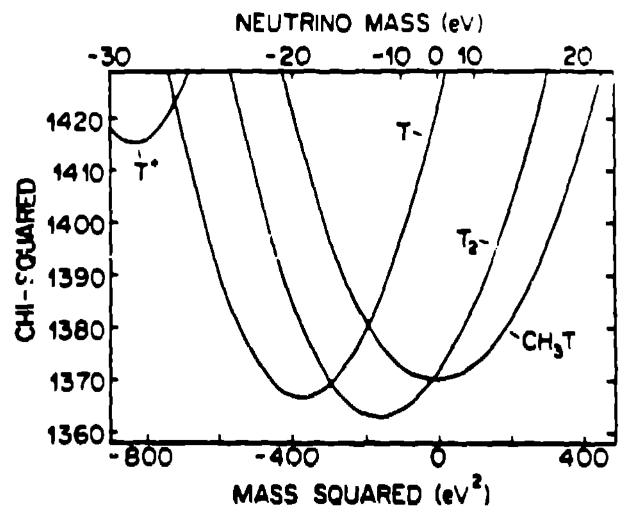

Fig. 2. χ^2 vs m_ν^2 from analysis of Fritschi et al.[6]. Note for different final state assumptions the large change in best fit m_ν, but small change in χ^2.

The absolutely critical role that final state effects play in determining an experiment's best value for m_ν can be seen in Fig. 2. This figure of χ^2 vs m_ν^2 from Fritschi et al.[6] displays various χ^2 curves assuming different final states configurations. Although there are almost no differences in the best χ^2 values for the different configurations there are significant differences in the best m_ν^2 values. For example assuming molecular final states instead of atomic final states results in a shift of the best value of m_ν by 15 eV.

2.1.2 Total resolution function. The total resolution function (TRF) is defined as the convolution of the instrumental resolution and the total source energy loss. In an analogous fashion to final state effects, an accurate knowledge of the TRF is absolutely imperative.

Most experiments have devised methods to directly measure instrumental resolution. But, ascertaining the energy loss contributions has proven more difficult. With solid sources the total energy loss is a combination of energy loss in the target, energy loss of electrons that backscatter from the source backing, and energy loss in any surface contamination.

A few comments on the parametrization of the TRF are warranted. The full width half maximum (FWHM) of the TRF is a very poor description of the distribution. For example the ITEP TRF shown in Fig. 3 has a FWHM of 22 eV but the second moment, σ^2, of the distribution is 2250 eV^2. (The effect of this size TRF on the spectrum if expressed in neutrino mass is ~67 eV.) However, one must also use caution in using the σ^2 parametrization and explicitly define the energy region used for its calculation. This is because σ^2 of TRFs that include backscattering tend toward infinity as the energy region used for the calculation becomes large. When making

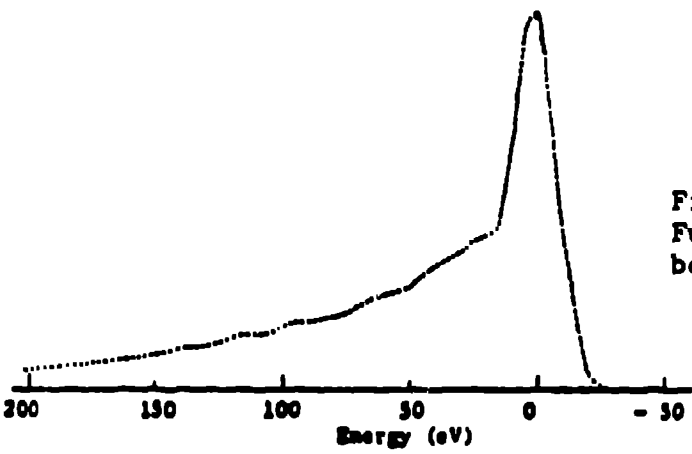

Fig. 3. Total Resolution Function of the ITEP tritium beta decay experiment.

comparisons between different experiments the best method is to examine the actual TRF and not just the FWHM or the second moment parameters. Finally, often when tritium beta decay experiments are being discussed there is emphasis on the instrumental resolution while source energy loss is ignored. Clearly the TRF of an experiment is the relevant distribution to examine.

2.2 Summary Of Measurement Considerations

A statistically significant result that either implies a finite neutrino mass or rules out a neutrino mass is meaningless if all systematic effects have not been accurately and completely accounted for. Hence, the elimination or minimization and total understanding of all systematic effects is crucial in obtaining a believable result.

If experiments push the m_ν value towards zero the limitations imposed by systematic effects will dominate and must not be ignored.

3. ANALYSIS CONSIDERATIONS

Before reviewing the experimental results a few comments with regards to the analysis of the data are in order. Most of the experiments analyze the data by simultaneously fitting several parameters of the Fermi decay probability function

$$N(E) = C\, F(Z,R,E)\, p_e\, E\, \Sigma_i w_i (E_o - E_i - E)[(E_o - E_i - E)^2 - m_\nu^2 c^4]^{1/2}$$
$$\times\ [1 + \alpha_1 (E_o - E) + \alpha_2 (E_o - E)^2] \quad ; \quad E \le E_o - E_i - m_\nu c^2$$

by using a maximum likelihood method. In their analysis, most of the experiments fit to the neutrino mass m_ν, the endpoint energy E_o, and amplitude C. They may additionally fit to a collection of the following parameters; the background *BG*, a linear correction coefficient α_1 and a quadratic correction coefficient α_2. The use of these coefficients α_1 and α_2 must have some physical motivation.

Finally, a few general comments on the analysis:

- The maximum likelihood estimator must employee the proper statistics. For example, in the Los Alamos analysis[7)], it was discovered from Monte Carlo simulation studies that using the Gaussian statistics based χ^2 estimator introduced a non-negligible systematic shift to the best fit m_ν value. The use of Poisson based maximum likelihood estimator eliminated the shift error.
- Regardless of the parameters fit, the results from the analysis should not depend (within statistics) on the portion of the spectrum analyzed.
- Determining the error of a result requires careful analyses of all systematic errors using the maximum likelihood analysis code. Attempting to make approximations and simplifications for analytical analyses of errors is not only dangerous but usually wrong.

4. CURRENT RESULTS

In addition to a new ITEP m_ν value, three experimental groups have reported limits on m_ν from tritium beta decay measurements in 1986. The unique aspects and salient features of these four experiments will be discussed below. Table 2 offers a summary of some of the pertinent parameters from these experiments. Because of space limitations, experiments reporting preliminary results and the less sensitive Si detector experiments will not be examined. (Reference 8 contains reports from many of these experiments.)

Table 2.

Expt.	Last 100 eV S:B	Last 100 eV Total Counts	TRF σ^{2*} eV^2	TRF FWHM eV	Source Thickness $\mu g/cm^2$	Source No Loss %	Limit or Value eV
LANL	4:1	.6k	540	36	0.1	83	< 27 95% CL
ITEP	16:1	130k	2250	22	~4	37	30 ± 2
Zurich	?	~1000k	550	27	~4	60	< 18
INS	1:1	5k	1197	14	1.5	60 - 65	< 32 95% CL

* σ^2 was calculated over the TRF energy range of +50 to -150 eV.

It is interesting to note (Table 1) that the groups that have results are using some type of magnetic spectrometers. Although the electrostatic spectrometer experiments have excellent instrumental resolution, thus far all of these experiments have encountered difficulties and delays, usually arising from background problems. It is encouraging however, that three of these experiments have started taking preliminary data with tritium sources and may produce results in 1987.

4.1 Los Alamos Experiment

Of the experiments with results or taking data the Los Alamos experiment is the only one using a gaseous molecular tritium source and hence the only experiment with model independent results. In addition to the clear advantage of using a source with simple, well understood final states, the use of a gaseous source eliminates backscattering and surface contamination that add uncertainties to solid source based measurements. Furthermore, the use of a pure tritium source yields the highest specific activity, thus minimizing source energy loss.

The Los Alamos apparatus, which has been described in detail elsewhere[7)], consists of an extended source and a toroidal spectrometer. The instrumental resolution function is directly measured using a short-lived (1.8 hours) gaseous ^{83m}Kr isomer 17.835(20) keV K-conversion line. Calculations to determine the energy loss contribution to the TRF are based directly on doubly differential cross-section for electrons scattering from H_2.

The Los Alamos data consist of four data sets, each of 3-4 days duration (Fig. 4). In the analysis of the data m_ν, E_0, C, BG, and α_2 were fit. The inclusion of the α_2 term was based on the energy dependent extraction efficiency of the apparatus. The uncertainty in the final result is predominantly statistical. An upper limit on the mass of the electron antineutrino is found to be 26.8 eV at the 95% confidence level (CL) or 23.3 eV at the 90% CL Improvements now in progress to the apparatus are expected to result in a sensitivity to neutrino mass in the vicinity of 10 eV.

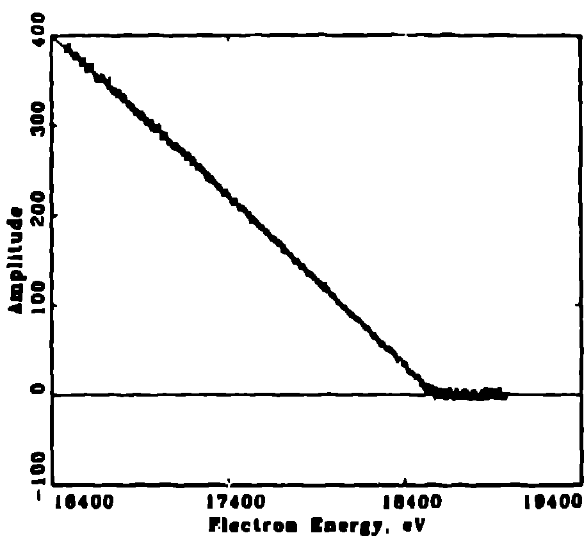

Fig. 4. Kurie plot of one of the LANL data sets.

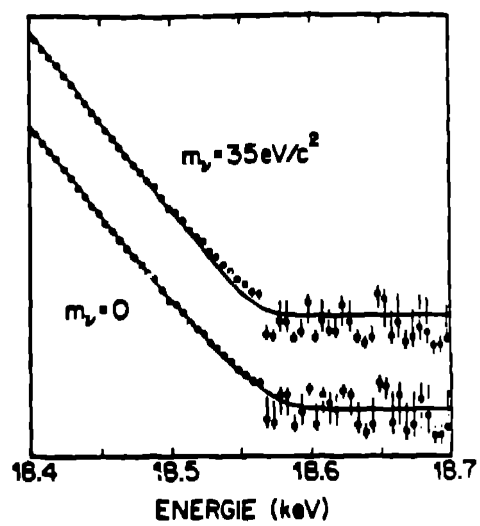

Fig. 5. Zurich data with fits for $m_\nu = 0$ and $m_\nu = 35$ eV.

4.2 ITEP Experiment

The ITEP experiment using a complex amino acid tritiated valine source and a toroidal spectrometer has implemented a number of improvements since their initial measurement. They have substantially improved their S:B ratio and implemented methods to directly measure their instrumental resolution function and source energy loss contribution. The fitting parameters m_ν, E_0, C, α_2, and (in the 1986 analysis) α_1 were used in the analysis. The model dependent result of 30 ± 2 eV is statistically significant, but systematic uncertainties remain, especially from the use of the complex valine source.

The ITEP experiment also claims a model independent limit on the neutrino mass of $17 < m_\nu < 40$ eV. This limit is obtained by analyzing the data while compressing or expanding the energy scale of the valine final state spectrum and observing at what points the fit E_o is incompatible with E_o determined from ion cyclotron resonance measurements of the T-^3He mass difference.

4.3 Zurich Experiment

Like the ITEP experiment, the results from the Zurich measurement are not statistics limited (Fig. 5), but their upper limit on m_ν of 18 eV (no confidence level quoted) is in direct disagreement with the ITEP result. Since the statistical evidence to support both claims is very strong, the difference between the two results must arise from systematic problems in one or both experiments. The instrumental resolution function of their toroidal spectrometer is calculated while the energy loss of their source (tritium implanted in carbon) is calculated from plasmon excitation theory using their measured tritium implantation depth. Backscattering is not included in the Zurich TRF, but is taken into account by using the α_1 fitting parameter during the analysis (m_ν, E_o, C, & BG are also fit). The final state configuration of CH_3T is assumed for their implanted source. New data with over ten times more statistics and better instrumental resolution has recently been acquired and new results should be forthcoming soon.

4.4 INS Experiment

The Tokyo experiment[9] uses an air core $\pi\sqrt{2}$ magnetic spectrometer and a novel mono-layer Cd salt of arachidic acid containing tritium. By replacing the natural Cd with ^{109}Cd, measurements with the Ag KLL Auger lines allow determination of instrumental resolution and of source energy losses. Although calculations of FS effects are in progress for the actual source, the present results used the identical valine final state calculations used by the ITEP group. The parameters m_ν, E_o, C, & α_2 were fit in the data analysis which yields a model dependent upper limit on m_ν of 32 eV at the 95% CL. The INS group plans to acquire increased statistics which should improve their current limit.

A few final observations on the present measurements:

- Exchanging the ITEP and Zurich TRFs would essentially produce an exchange of their results.
- Notice in Table 2 that the values for source thickness and percent of electrons emerging from the source with no energy loss seem to be

inconsistent for the solid source based ITEP, Zurich, and INS experiments.

5. CONCLUSIONS

Based on current results the $\bar{\nu}_e$ mass question is still open. In 1987 a more definitive answer on the $\bar{\nu}_e$ mass should be reached. However, one must beware of the problem of "intellectual phase locking" where results agree with the expected value and are not rigorously examined. All of the experiments must be critically examined regardless of their results. Sufficient statistics are necessary for a reliable measurement, but as the limit on m_ν is further reduced the role of systematic effects will become increasingly important. Elimination or the direct measurements of systematic effects is the crucial requirement in making a reliable determination of the $\bar{\nu}_e$ mass.

REFERENCES

1. V. Lyubimov, in *Nuclear Beta Decays and Neutrino*, eds. T. Kotani, H. Ejiri, & E. Takasugi, p. 273 (World Scientific, 1986).
2. V. A. Lyubimov et al., Zh. Eksp. Teor. Fiz. 81, 1158 (1981).
3. R. D. Williams and S. E. Koonin, Phys. Rev. C27, 1815 (1983).
4. R. L. Martin and J. S. Cohen, Phys. Lett. 110A, 95 (1985).
5. W. Kolos et al., Phys. Rev. A31, 551 (1985); O. Fackler et al., Phys. Rev. Lett. 55, 1388 (1985); K. Szalewicz et al., submitted to Phys. Rev. A. (1986).
6. M. Fritschi et al., Phys. Lett 173B, 485 (1986).
7. T. J. Bowles et al., in *Nuclear Beta Decays and Neutrino*, eds. T. Kotani, H. Ejiri, & E. Takasugi, p. 304 (World Scientific, 1986); D. A. Knapp, Ph.D. Dissertation LA-10877-T, Princeton University, 1986 (unpublished).
8. *Nuclear Beta Decays and Neutrino*, eds. T. Kotani, H. Ejiri, & E. Takasugi (World Scientific, 1986).
9. H Kawakami et al., in *Nuclear Beta Decays and Neutrino*, eds. T. Kotani, H. Ejiri, & E. Takasugi, p. 294 (World Scientific, 1986).